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Radio Emission as a Test of the Existence of Intermediate Mass Black Holes in Globular Clusters and Dwarf Spheroidal Galaxies

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ABSTRACT

We take the established relation between black hole mass, X-ray luminosity, and radio luminosity and show that intermediate mass black holes, such as those predicted to exist at the centers of globular clusters, will be easily identifiable objects in deep radio observations. We show that the radio observations will be far more senstive than any possible X-ray observations. We also discuss the likely optical photometric and spectroscopic appearance of such systems in the event that radio detections are made.

Key words: globular clusters:general – globular clusters:individual:Omega Cen – accretion, accretion discs – black hole physics – radio continuum:general

1 INTRODUCTION

Intermediate mass black holes may represent the link between the stellar mass black holes seen in the Milky Way (which are probably all less massive than $20M_\odot$ - see McClintock & Remillard 2003) and the supermassive black holes thought to exist in the centers of galaxies (which are mostly more massive than $10^6 M_\odot$, but see e.g. Fillipenko & Ho 2003 for a galaxy with a slightly less massive nucleus). It is possible that the AGN have grown from $\sim 300M_\odot$ black holes formed from core collapses of Population III stars (see e.g. Fryer, Woosley & Heger 2001). The centers of dense star clusters may also produce intermediate mass black holes, either through the coalescence of massive stars into a single extremely massive star which then undergoes core collapse into a black hole (Portegies Zwart & McMillan 2002; Gürkan, Freitag & Rasio 2004) or through mergers of smaller black holes (Miller & Hamilton 2002). Searches for these black holes have, to date, proved inconclusive.

Evidence for the existence of black holes in binary systems in the Milky Way has been based largely on measuring the masses of X-ray binaries from their rotation curves along with estimates of their inclination angles and donor star masses (see Orosz 2003 for a review). When the measured mass is larger than $3M_\odot$, the object is assumed to be a black hole. In galactic nuclei, measurement of the mass of the central dark object has come from a handful of techniques. For bright active galactic nuclei (AGN), reverberation mapping, which uses the light travel times to regions with a particular ionization level (see e.g. Peterson 1998 for a review), can be applied. For galaxies with weak or undetected AGN activity, other techniques are required. One such method is measurement of the rotational velocity and the velocity dispersion of the stars or gas in a galaxy's disk; gas measurements are capable of probing smaller scales, while stellar measurements are far less likely to be affected by non-gravitational pertubrations and hence are more reliable (see Kormendy & Richstone 1995 for a review). Furthermore, rotation curves are measured on distance scales larger than that where the black hole's mass dominates a galaxy's total enclosed mass.

A popular alternative is to use only the velocity dispersion of the galaxies' bulge stars (Ferrarese & Merritt 2000; Gebhardt et al. 2000b), a quantity which correlates well with the rotational velocity curve and can be easier to measure. Finally, it has recently been found that the light profile of the inner regions of elliptical galaxies and of the bulges of spiral galaxies deviates slightly from the de Vaucouleurs profile, and that these deviations correlate well with the central black hole mass measured using other techniques (Graham et al. 2001). The results of Graham et al. (2001) are not well understood on theoretical grounds.

All these techniques are rather difficult to apply to black holes in globular clusters. While rotation measurements for globular clusters are possible (see e.g. Gebhardt et al. 2000a; Anderson & King 2003), they are rather difficult to obtain and have not yet been sufficient for proving the existence of a central black hole. More recent attempts to measure the dark masses at the centers of Local Group globular clusters have focused on measuring which regions of velocity-position phase space are occupied by stars and comparing these observations with model predictions (Gerssen et al. 2002).

Even M15, which shows the best evidence for rotation has a velocity dispersion comparable to its rotational velocity in its center (Gebhardt et al. 2000a; Gerssen et al. 2002). Given the large velocity dispersion of the stars in globular clusters, and the relatively small number of stars, even with perfect measurements of the velocities of a very large sample of the stars, it might not always be possible to measure the gravitationational potential well enough to measure the mass of a central dark object (see e.g. the discussion in Drukier & Bailyn 2003). Attempts have been made to use large kinematic data sets to place constraints on the masses of central compact objects, but the uncertainties are quite large and the results are highly model dependent (e.g. van der Marel 2001;

Gerssen et al. 2002,2003). Without reliable measurements to calibrate a relation, use of the Ferrarese & Merritt technique or of the Graham et al. technique would be quite dangerous.

A few techniques have also been suggested that apply only to globular clusters. One such method is to search for high velocity stars within the cluster, but the predictions for how many high velocity stars should exist given a certain black hole mass depend on an extremely detailed treatment of the stellar dynamics (Drukier & Bailyn 2003). Another possibility is the use of exotic ejected binary systems as evidence for the existence of the black hole-black hole binary system in the core. In NGC 6752, the binary pulsar system PSR J1911-5958A is seen 3.3 half mass radii from the core of the globular cluster (D'Amico et al. 2002). The rather long period circular orbit suggests that the ejection was caused by a recoil of a binary system substantially larger than the pulsar binary, but with a large binding energy. A natural possibility for such a binary is one containing two black holes (Colpi, Possenti & Gualandris 2002). The cluster also has a high central mass-to-light ratio (D'Amico et al. 2002). The evidence for a black hole-black hole binary at the core of this cluster is highly circumstantial, though, and should be confirmed by some other techniques before the hypothesis is accepted.

The use of stellar kinematics to identify intermediate mass black holes in globular clusters poses challenges not found either in binary systems or in galaxy centers. It would thus be wise to consider additional techniques, both to improve the capability of discovering these objects, and to bolster confidence in detections made using stellar kinematics. Recent work on correlations between the X-ray and radio properties of both X-ray binaries and AGN indicates that the ratio of radio to X-ray power increases with black hole mass and decreases with accretion rate (Gallo, Fender & Pooley 2003; Merloni, Heinz & Di Matteo 2003; Falcke, Körding & Markoff 2003; Maccarone, Gallo & Fender 2003). Given that the central black holes in globular clusters are likely to be substantially more massive than stellar mass black holes, and are certainly accreting at low fractions of the Eddington luminosity (since none have yet been detected in the X-rays), these results indicate that radio measurements may hold the key for detecting the central black holes in globular clusters. In this Letter, we outline the predictions made for radio flux from central black holes in globular clusters given certain constraints on the X-ray luminosity.

2 THE CORRELATIONS

Two important results have been found recently that indicate that radio, rather than X-rays may be the most efficient waveband for identifying accreting intermediate mass black holes, especially in Milky Way globular clusters. The first is the result of Gallo, Fender & Pooley (2003), which shows, for stellar mass black holes, that while the X-ray and radio luminosities of low/hard state objects (see Nowak 1995 for a discussion of spectral state and Fender 2004 for a review of the radio properties of X-ray binaries) are tightly correlated, the radio luminosity falls off more slowly at low luminosity than does the X-ray luminosity. Thus, at lower luminosities, the radio emission becomes relatively easier to detect compared with the X-ray emission. The second key recent discovery is that the radio to X-ray flux ratio increases with the mass of the accreting black hole (e.g. Heinz & Sunyaev 2003; Merloni, Heinz & Di Matteo 2003). This indicates that for intermediate mass black holes, the radio emission will be substantially brighter than for stellar mass black holes at the same luminosity, making them again easier to detect.

The correlations do break down at high fractions of the Eddington luminosity, both in X-ray binaries which accrete from a companion star, and in AGN, which like black holes at the centers of globular clusters, are most likely to accrete from the interstellar medium. High/soft states, where the X-ray spectrum is dominated by a component well modeled by a geometrically thin, optically thick accretion disk (Shakura & Sunyaev 1973) typically set in above about 2% of the Eddington luminosity, although some scatter is likely due to hysteresis effects in state transition luminosities (Maccarone 2003; Maccarone & Coppi 2003). In the high/soft states of X-ray binaries, the radio emission is highly suppressed (Tananbaum et al. 1972; Fender et al. 1999), probably because geometrically thin disks have weaker poloidal magnetic fields than do geometrically thick accretion flows, and such magnetic fields are required for jets to be launched (Livio, Ogilvie & Pringle 1999; Meier 2001). The radio emission turns back on at higher fractions of the Eddington rate. The results of Fender et al. (1999) for X-ray binaries have recently been extended to AGN, which also show suppressed jet activity between about 2 and 20% of the Eddington accretion rate (Maccarone, Gallo & Fender 2003). Nonetheless, any IMBH within the Milky Way's globular clusters should be in the low/hard state; one in a higher luminosity state would be quite bright and would have already been known based on its X-ray properties unless it were highly absorbed.

3 X-RAY CONSTRAINTS FOR GLOBULAR CLUSTERS

Recent theoretical work has suggested that all globular clusters should have central black holes with masses of order 10^{-3} times the stellar mass in the cluster, due to mergers of black holes (Miller & Hamilton 2002). Additionally, young dense stellar clusters are also expected to produce black holes with 10^{-3} times the stellar mass in the cluster through stellar mergers leading to the production of a single highly massive star which evolves quickly into a black hole (Portegies Zwart & McMillan 2002; Gürkan et al. 2004). It is expected, however, that the young stellar clusters dense enough to have these stellar mergers in their cores will evolve in a different way than the globular clusters we see today. These systems are thus not relevant to discussions specific to globular clusters, but the basic point presented here, that intermediate mass black holes at low luminosities will be more easily detected in radio than in X-ray is as relevant for these black holes as it is for those that might found in globular clusters.

Given the theoretical predictions for the masses of black holes in globular clusters and the proof from pulsar measurements that certain globular clusters have substantial amount of gas (i.e. about 0.1 atoms/cm^3 at a temperature of about 10^4 K - see e.g. Freire et al. 2001), one can compute a Bondi accretion rate. Given the expected radiative efficiency at low accretion rate, the expected X-ray luminosity will be quite low (detectable in some clusters with the typical *Chandra* exposure times, but faint enough that spectroscopy will be difficult and it will be virtually impossible to distinguish one of these sources from the other types of less exotic X-ray sources found in globular clusters based solely on the position and X-ray properties of the source).

A couple of the Milky Way's globular clusters (47 Tuc and M15) show enough millisecond pulsars that the gas content can be estimated by variations in the dispersion measure through the cluster; since these measurements are consistent with what it expected

from stellar mass loss, it seems reasonable to assume that the similar values are present in other clusters (Freire et al. 2001). Recent *Chandra* observations of M15 have shown that there is no "nucleus" of the cluster seen in X-rays to a limit of 5.6×10^{32} ergs/sec, a factor of a few thousand below the expected Bondi accretion rate assuming a radiative efficiency of $0.1c^2$(Ho, Terashima & Okajima 2003). This factor is roughly in line with the radiative efficiency corrections expected from either an advection dominated accretion flow (Narayan & Yi 1994) or a jet dominated accretion flow (Fender, Gallo & Jonker 2003). Additionally, theoretical work more detailed than Bondi & Hyole (1944) suggested that the Bondi accretion rate may represent an overestimate of how much accretion actually takes place. Such claims are supported by the lack of detections of isolated neutron stars accreting from the ISM and the very low luminosities of the central black holes in many elliptical galaxies (Perna et al. 2003; Di Matteo et al. 2000). Furthermore, Ho et al. (2003) assumed a black hole mass of 2000 $M_\odot$, while 0.1% of the cluster mass for M15 is about 440 $M_\odot$, which would reduce the Bondi rate by an additional factor of about 20. An upper limit has also been placed on the X-ray luminosity of the core 47 Tuc at 10^{31} ergs/sec, which gives similar constraints on the radiative efficiency, assuming that the black hole mass is a few hundred solar masses (Grindlay et al. 2001).

4 PREDICTIONS FOR THE RADIO FLUX

From the relation of Merloni et al. (2003), we find that

$$F_{5GHz} = 10\left(\frac{L_x}{3\times10^{31}\mathrm{ergs/sec}}\right)^{0.6}\left(\frac{M_{BH}}{100M_\odot}\right)^{0.78}\left(\frac{d}{10\mathrm{kpc}}\right)^{-2}\mu\mathrm{Jy} \quad (1)$$

A slightly higher radio flux can be derived from the relation of Maccarone, Gallo & Fender (2003) which removes the objects thought to be in the high/soft state.

The sensitivities of the deepest existing radio fields (none of which are of globular clusters) are about 8 μJy rms, so detections can be made above about 25μJy. For the controversial case of M15, where Gebhardt et al. (2000a) claimed a 2500 $M_\odot$ black hole, and which is located about 10 kpc from the Sun (Harris 1996), an X-ray luminosity at the upper limit of the *Chandra* data would yield a radio flux of about 0.7 mJy. Radio observations with 8 μJy rms would be able to place the same constraints on the whether a 2500 $M_\odot$ black hole exists as X-ray measurements a factor of about 250 deeper in flux than the current ones. Those *Chandra* observations already required about 30 ksec of time. A single 12 hour observation with the VLA will then place a stronger constraint on whether there exists a $\sim 1000M_\odot$ black hole in M15 than would spending the entire mission lifetime of Chandra on the same field of view.

Once a strong candidate is observed, there should be a few tests performed to ensure that the radio source is not a pulsar. The first, obviously, is to look for pulsations. The second would be to measure the radio spectrum - jets from low/hard state black holes should have flat radio spectra, while pulsars have quite steep radio spectra. A final test is that pulsars scintillate quite strongly, while the jet from a low luminosity intermediate mass black hole should be far too large to scintillate (see Narayan 1992 for a discussion of scintillation). Additionally, pulsars are strongly polarized (see e.g. Manchester, Han & Qiao 1998), while low/hard state radio spectra are polarized at only the 1-2% level (Fender 2001).

Similar reasoning can be applied to the Milky Way's dwarf spheroidal galaxies with only a few small changes. These systems are even harder to work with than the globular clusters for typical measurement techniques, since the density of stars in the center is much lower. Furthermore, the theoretical expectations for the masses of central black holes have not been worked out in as much detail. Finally, only the Sagittarius dwarf is near enough that it is likely to be detectable with this technique.

5 PREDICTION FOR THE OPTICAL/INFRARED APPEARANCE

Low/hard state X-ray binaries and from luminosity AGN show a flat-to-slightly inverted radio spectrum (i.e. $\alpha \lesssim 0$, where $F_\nu \propto \nu^{-\alpha}$), presumably due to synchrotron self-absorption of a more intrinsically steep power law, in agreement with the conical jet model (Blandford & Königl 1979). The cutoff frequency where the jet becomes optically thin is found to be in the mid-to-near-infrared for jets from X-ray binaries (Corbel & Fender 2002), and should be at a somewhat longer wavelength for a globular cluster black hole which is weak in X-rays, since the cutoff frequency, ν_τ, scales as $M_{BH}^{1/3}(\frac{\dot{m}}{\dot{m}_{EDD}})^{2/3}$ for a radiatively inefficient accreting black hole with a typical spectral index (i.e. $\alpha = 0.5$) for the optically thin component of the jet emission (see equation 14 of Heinz & Sunyaev 2003). One should then expect that the optical emission from the jet will be optically thin, and have a spectral index of about $\alpha = 0.5$. Given a cutoff at 10 μm for the globular cluster black holes' jets, one finds that:

$$V = 23.0 - 2.5\log\left(\frac{F_{5GHZ}}{10\mu\mathrm{Jy}}\right), \quad (2)$$

or combining with equation 1

$$V = 23.0 - 1.5\log\left(\frac{L_x}{3\times10^{31}\mathrm{ergs/sec}}\right) - 1.95\log\left(\frac{M_{BH}}{100M_\odot}\right) + 5\log\left(\frac{d}{10\mathrm{kpc}}\right) \quad (3$$

and the optical colors should be approximately $V-I$=0.3 and $V-K$=1.2 (all assuming no reddening). Given the density of stars in the core of a globular cluster and the difficulty in performing accurate photometry there, optical photometry is a less robust technique for proving that a black hole is present than radio detection. Furthermore, there may be additional non-jet flux in this range of wavelengths due to emission from a pre-shock jet region (e.g. Markoff, Falcke & Fender 2003) or due to optical synchrotron emission from a magnetically or otherwise powered corona above the accretion disk (see e.g. Merloni, Di Matteo & Fabian 2000). A perhaps more robust proof would come from spectroscopy; detection of a faint red star which shows no evidence for any spectral lines (since the continuum should be dominated by non-thermal emission) would make non-accretion models for the optical emission rather difficult. It is unlikely that the thermal component from the geometrically thin part of the accretion disk will contribute substantially to the flux; the thin disk components of low/hard state black holes begin to emit a substantial fraction of the total luminosity only in the ultraviolet (see McClintock et al. 2001), and in any event, it is not clear whether the accreted interstellar matter will have enough angular momentum even to form a disc at large radii. Spectroscopic studies of faint stars in the cores of globular are rather difficult to perform, so the spectroscopic method is likely to be of use only to confirm the results of radio and photometric work, and not as the starting point for the search for black holes in globular clusters.

6 WHICH GCS ARE THE BEST CANDIDATES?

We make crude estimates of the expected radio fluxes, under the following assumptions: the black hole mass is 0.1% of the globular cluster mass, the actual accretion rate is 0.1% of the Bondi rate (the value considered most likely in Perna et al. 2003), a gas density of 0.15 H cm^{-3} (approximately the value measured for both 47 Tuc and M15) and the radiative efficiency scales as shown in Fender, Gallo & Jonker (2003; FGJ). We note, also, that if there is a binary black hole in the center of the globular cluster, the Bondi rate may be considerably reduced due to orbital motions. This will be a problem only if the mass ratio between the two black holes is less than about 10 this problem or if the central binary is quite hard. Miller & Hamilton (2002) find that if black hole binaries exist in globular clusters, they are likely to have large mass ratios and to spend most of their lifetimes in wide separations, so the problem of the binary orbit is unlikely to be a serious one.

It is suggested in FGJ that the accretion power goes into two components - a relativistic jet and X-ray emission, and it is shown that the jet power will scale as $AL_X^{0.5}$, where A is a constant found to be at least 6×10^{-3} for black holes and L_X is the X-ray luminosity. The total luminosity, L_{tot} is then equal to $AL_X^{0.5}+L_X$. Assuming that the efficiency in converting accreted mass into energy is the standard 10%, then the radiative efficiency in the X-rays will be:

$$\eta=(0.1)\times\left(1+\frac{A^2}{2L_{tot}}-A\sqrt{\frac{A^2}{4L_{tot}^2}+\frac{1}{L_{tot}}}\right), \qquad (4)$$

and we set A to the most conservative value for jet power of 6×10^{-3}, and where L_{tot} is expressed in Eddington units. We note that the radiative efficiency scales with the accretion rate in quite a similar way in the JDAF and ADAF models.

The Bondi rate (Bondi & Hoyle 1944) is given in convenient form by Ho et al. (2003):

$$\dot{M}_{BH}=3.2\times10^{17}\left(\frac{M_{BH}}{2000M_\odot}\right)^2\left(\frac{n}{0.2\mathrm{cm}^{-3}}\right)\left(\frac{T}{10^4\mathrm{K}}\right)^{3/2}\mathrm{gs}^{-1}. \qquad (5)$$

We make two sets of calculations, assuming the accretion rate to be 10^{-2} and 10^{-3} of the Bondi rate (the proposed maximum accretion rate and most likely accretion rate from Perna et al. 2003). We note that for the higher accretion rate, the predictions for the X-ray luminosity and the radio flux from 47 Tuc are in excess of the observed upper limits, so unless the black hole mass in 47 Tuc is anomalously low, the values in the table for the 10^{-2} Bondi accretion rate case are too optimistic. It also seems likely that a 2.4 mJy source in Omega Cen would have been missed, but there are not any good upper limits published, and Omega Cen is sufficiently far south to have been missed by surveys such as NVSS.

We take the data for the Milky Way's globular clusters from Harris (1996). The mass is not reported directly, so we convert from integrated absolute visual magnitude M_V to mass using a mass-to-V-light ratio of 1.8 (Piatek et al. 1994). The globular cluster's mass is then:

$$M_{GC}=10^6M_\odot10^{-(M_V+10)/2.5}, \qquad (6)$$

and the central black hole mass is predicted, from Miller & Hamilton (2002), to be:

$$M_{BH}=1000M_\odot10^{-(M_V+10)/2.5}. \qquad (7)$$

The predicted radio and X-ray fluxes for 15 good candidate globular clusters are presented in table 1, along with the estimates of the black hole mass and distance used. We include some objects calculated to lie below the detection limit from a reasonable integration largely because the estimate of the fraction of the Bondi accretion rate that is actually accreted computed in Perna et al. (2003) is highly uncertain, and it is well within the realm of possibility that the expected fluxes could be at least a factor of 10 higher. The strongest observational point in favor of the claim by Perna et al. (2003) is that no isolated neutron stars accreting from the interstellar medium were detected by ROSAT; in fact there are numerous unidentified sources in the ROSAT catalogs, and some fraction could be these isolated neutron stars.

We note that M54 in particular might be a substantially better candidate than the table suggests - it is the nucleus of the Sagittarius dwarf spheroidal galaxy, and hence setting its black hole mass value to 10^{-3} times the globular cluster's mass, rather than 10^{-3} times the galaxy's mass may be a substantial underestimate. Since, in our model, the radio luminosity scales roughly as M^2, an underestimate of the black hole mass by a factor of 10 has profound implications on the expected radio flux. We also note that NGC 6440 and NGC 6441 have bright low mass X-ray binaries (Liu, van Paradijs & van den Heuvel 2001), which could seriously affect the accuracy of X-ray flux measurements of their nuclei. Furthermore, the expanded VLA (see http://www.aoc.nrao.edu/evla/index.shtml) is expected to have a sensitivity limit a factor of five times lower than the current VLA, and should have a higher angular resolution to ensure that extragalactic confusion will still not be a problem.

The two clusters with the highest predicted flux levels are far enough south that they cannot be observed with the VLA. The observations which come closest to the predicted flux limits of any of these clusters are the ATCA observations of 47 Tuc (Fruchter & Goss 2000; McConnell & Ables 2000). These reach an rms flux density of only about 30 μJy, and are taken at $\approx$ 20 cm wavelengths where the angular resolution is poor, and pulsars are relatively brighter further reducing their usefulness for finding a black hole's radio emission. We find no reports in the literature regarding deep radio observations of Omega Cen, either; the ATCA archives contain only 10-hour observations of the outskirts of the cluster, and these observations are in taken in a multi-channel spectral line mode with low bandwidth that makes the data not sufficiently deep for detecting continuum at the levels predicted. It seems possible that the brightest clusters may have radio emission from central black holes that is detectable given a deep, optimally designed observation, but which could not be detected with existing data.

7 CONCLUSIONS

Determining whether globular clusters contain intermediate mass black holes is a key problem in astronomy. In this Letter, we have outlined a technique for using radio and optical photometry to test whether there are good candidates for intermediate mass black hole in the centers of globular clusters. Furthermore, this technique is truly sensitive to the mass of the central compact object, unlike most kinematic methods which are merely sensitive to dark matter concentrations. We have also shown that the results are likely to apply to dwarf spheroidal galaxies. Most importantly, we have shown that there exists a strong possibility for detecting at least a handful of the putative central black holes of Milky Way globular clusters through their radio emission in the near future, and have shown that radio emission is likely to be the most effective way to identify the strongest candidates for having central black holes. Obviously there are considerable uncertainties regarding the predicted level of radio emission, but given a detection in the radio and either

GC	M_{BH}	d	$L_{X,-3}$	$F_{5GHz,-3}$	$F_{5GHz,-2}$	Common name	comments
NGC 5139	1250	5.1	1.1×10^{31}	154	2400	Omega Cen	
NGC 104	560	4.3	1.0×10^{30}	27	430	47 Tuc	$L_X < 10^{31}$ from obs.
NGC 6656	240	3.2	8.1×10^{28}	6	90	M22	
NGC 6388	810	11.5	3.1×10^{30}	10	160		
NGC 6266	450	6.7	5.4×10^{29}	7	100	M62	
NGC 2808	550	9.3	9.8×10^{29}	6	90		
NGC 6441	470	9.7	6.1×10^{29}	3	50	LMXB	
NGC 6273	410	8.5	4.0×10^{29}	3	50	M19	
NGC 6402	390	8.7	3.4×10^{29}	3	40	M14	
NGC 5904	320	7.3	1.9×10^{29}	2	40	M5	
NGC 7078	440	10.2	5.0×10^{29}	3	40	M15	$L_X < 5\times10^{32}$ from obs.
NGC 6440	300	8.	1.6×10^{29}	2	30	LMXB	
NGC 6715	960	26.2	5.3×10^{30}	3	50	M54	Sag dwarf - BH mass may be higher
NGC 6626	210	5.7	5.1×10^{28}	1	20		M28
NGC 6205	250	7.0	9.3×10^{28}	1	20		

Table 1. The globular clusters expected to be brightest in radio. The black hole mass is expressed in solar units, the distance in kiloparsecs, the X-ray luminosity in ergs/sec and the radio flux in μJy; raw data is taken from Harris (1996) and the computation of the parameters is described in the text. $F_{5GHz,-3}$ refers to the prediction assuming the accretion rate is 0.1% of Bondi and $F_{5GHz,-2}$ refers to the prediction assuming 1% of Bondi. The X-ray luminosities assuming the 1% of Bondi accretion rate are all about 100 times the luminosities assuming 0.1% of Bondi accretion rates, since the X-ray efficiencies are all in the $\dot{m}^2$ regime.

a detection or a strong upper limit in the X-rays, it may be possible to provide good evidence for the existence of an intermediate mass black hole in a globular cluster or a dwarf spheroidal galaxy.

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